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AGB - STAR EVOLUTION

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ABSTRACT (U)

Asymptotic giant branch stars are red supergiant stars of low-to-intermediate mass. This class of stars is of particular interest because many of these stars can have nuclear processed material brought up repeatedly from the deep interior to the surface where it can be observed. A review of recent theoretical and observational work on stars undergoing the asymptotic giant branch phase is presented.

I. INTRODUCTION

The term asymptotic giant branch (AGB) originally referred to globular cluster stars located on a sequence in the H-R diagram which appeared to merge asymptotically with the giant branch at high luminosity. With time, the meaning of the term has been generalized to now refer to the evolution of any red giant star that possesses a degenerate carbon-oxygen core. AGB stars are characterized by one of two evolutionary states. Early AGB stars are dominated by a powerful He-burning shell while the H-burning shell is either inactive or very weak. Mature AGB stars have two active shell sources closely spaced in mass with the H-burning shell being dominant most of the time. The H-burning shell is normally active at about a hundredth of the luminosity of the H-burning shell; however, the

He-burning shell is unstable and it will periodically undergo a thermal runaway known as a thermal pulse or He-shell flash. A thermal pulse will extinguish the H-burning shell, and it could lead to some of the products of He-burning being dredged up to the surface of the star. Some important parameters of AGB stars are:

LUMINOSITY	$-7.3 < M_{bol} < -3$
	$3.0 < \log L/L_{\odot} < 4.8$
TEMPERATURE	$3.4 < \log Te < 3.6$
	$2500K < Te < 4000K$
RADIUS	$200 < R/R_{\odot} < 1000$
CORE MASS	$0.5 < M_{co}/M_{\odot} < 1.4$

Single stars with an initial mass in the range from slightly less than $1M_{\odot}$ to somewhere in the range of 5 to 9 $M_{\odot}$ will evolve into the AGB phase. More massive stars will avoid the AGB phase by igniting carbon in their cores before they becomes electron degenerate while low mass stars below the limit will not have had sufficient time during the age of the universe to evolve to the AGB. For binaries the situation is more complex and the question can either component evolve into the AGB phase will depend on the initial seperation and masses of the two stars.

Excellent detailed reviews of the pre-AGB and AGB evolutionary phases of single stars can be found in references 1-6. As a result, this information will not be repeated here, instead a brief summary of work completed since these reviews were published is presented. As a practical working point this paper will focus on developments from 1983 onward.

II. NEW THEORETICAL DEVELOPMENTS

A. Pre-AGB Evolution

One of the more interesting recent developments concerning the modeling of stellar evolution is the application of connective overshoot and semiconvection to the H-burning (references 7-9) and He-burning (references 7-10) convective core. Both convective overshoot and semiconvection provide more fuel to the convective core compared to cases where these effects are not included, and as one would expect, the lifetimes of various pre-AGB phases are changed. In addition during a given evolutionary phase a stellar model will attain a greater luminosity and will evolve onto the AGB with a larger degenerate carbon-oxygen core. In a way convective overshoot and semiconvection cause a stellar model to act as if it were more massive than it really is. For example, M_{up} the maximum mass a star can have that can evolve onto the AGB is about $9M_{\odot}$ in the standard evolutionary calculation while the limit may drop to as small as $5M_{\odot}$ when convective overshoot and semiconvection are included.[7,10]

While the application of convective overshoot and semiconvection to stellar evolution models shows promise with regards to low and intermediate mass stars, there is controversy as to when to apply these effects and the degree to which they are present (see especially reference 11). For example reference 7 applies convective overshoot to both the H-burning and He-burning convective core phases while reference 10 applies convective overshoot and semiconvection to only the He-burning convective core. Both approaches produce similiar models that evolve onto the AGB, but the previous pre-AGB evolutionary behavior is quite different especially with regards to the lifetimes of the various phases. Comparisons with observations may help to resolve some of the controversary.

Another fascinating development is the effect of a binary companion on the evolution of a star as discussed in references 5 and 12. The effects of mass transfer and system mass loss can drastically alter the evolutionary behavior from that expected of a single star so that the AGB phase may not be attained or it may be achieved by accretion after the star has become a white dwarf. Such accretion could permit the core of an AGB star to grow past the Chandrasekhar limit of $1.4M_{\odot}$ and therby result in a carbon deflagration supernova.

B. AGB Evolution

New models of AGB stars have been evolved especially for stars having an initial mass $\leq 3\ M_{\odot}$ [13-19] The third dredge-up phase is now found to occur at lower core masses and total stellar masses than previously thought [4,6,16,18] which is more consistent with the lower lumonosity limit of the observed distribution of carbon stars. For dredge-up to occur, it is necessary to have ℓ/H_p be > 1 in the calculations. In addition for models of low Z and small envelope mass, the effect of carbon recombination on the opacity during the power down phase of the He-burning shell can result in the formation of a semiconnective region which can mix together carbon and hydrogen. [4,6,19,15] When the hydrogen-burning shell reforms this mixed region is converted into ^{13}C which is later absorbed into the helium-burning convective shell during the next thermal pulse. This mechanism provides a neutron source for S-processing via the $^{13}C(\alpha,n)^{16}O$ reaction which can operate at much cooler temperature than the $^{22}Ne(\alpha,n)^{25}Mg$ reaction. It appears that the maximum temperature attained by the helium-burning shell for stars with $M_{co} < 0.8M_{\odot}$ is too cool to make effective use of the $^{22}Ne(\alpha,n)^{25}Mg$ reaction.

Other developments include a new look at the core-mass luminosity relation for low mass stars, [13, 16] and the evolution of a $3M_{\odot}$ model from the main sequence to the AGB to the white dwarf stage, [19] and the role of post AGB helium-shell flashes causing a "born again" AGB phase. [6] Private conversations with researchers reveal much work in progress which indicate this topic is certainly a fruitful one for future research.

C. Nucleosynthesis and the S-Process

As discussed in reference 4 the details of the dredge-up process and the effect of multiple thermal pulses allowing some material to have repeated neutron exposures have in principle the right ingredients to explain the solar system distribution of the elements. However, attempts to achieve this explaination have run into problems primarily because of the high temperature ($T > 3 \times 10^8$K) needed to drive the $^{22}Ne(\alpha,n)^{25}Mg$ reaction. Models which can achieve these high temperatures suffer from a dearth of observational counterparts, while models which have observational counterparts (such as the carbon stars) are unable to burn much of the ^{22}Ne. For example reference 20 finds that a helium-burning shell temperature of 310×10^6K would be required to explain the solar system distribution of the elements if it were to come from stars having core masses of 0.6 to 0.8 $M_\odot$. This is at least 10×10^6K hotter than any model in that core range has been able to achieve. Since the reaction rate for the $^{22}Ne(\alpha,n)^{25}Mg$ is uncertain, an increase in the rate would help to lower the needed burning temperature to perhaps the temperature range achieved by current models, however, this remains to be seen. References 21-26 represent a sample of current work on various aspects of the S-process in intermediate mass stars.

While the $^{13}C(\alpha,n)^{16}O$ reaction provides an alternate source of neutrons, the mechanism for production of ^{13}C is only likely to work for low mass stars with small envelope masses. In addition the size of the neutron absorption cross section for the relevant nuclei around ^{13}C will not provide the proper regulation of the nuetron flux (unlike the case for ^{22}Ne) so that the S-processes elements produced will be unlikely to have a solar system distribution. Despite these theoretical problems nature is clearly telling us that the S-process is taking place because of the presence of ^{99}Tc in the atmospheres of some AGB stars. Clearly the problem has yet to be solved.

III. NEW OBSERVATIONAL DEVELOPMENTS

Observational studies of AGB stars have shown that carbon stars have a luminosity distribution of $-4 > M_{bol} > -6$ [27] which raises the question where are the brighter AGB stars predicted by theory? Some studies of AGB stars in clusters and field regions of the Magellanic Clouds have shown a lack or scarcity of AGB stars more luminous than $M_{bol} = -6$ [9,27,28,29], however, references 30-34 have found that AGB stars do exist up to the theoretical limit of $M_{bol} = -7.3$. These bright AGB stars are not seen as carbon stars, but rather as long period variables and they appear to be about a factor of 10 less abundant than standard theory predicts. The lower than expected number of bright AGB stars has been interpreted as indicating the lifetime of a star on this part of the AGB is relatively short on the order of 10^5 yr with mass loss being evoked as the cause. Steady mass loss rates on the AGB are observed to be large and there exists the possibility that the entire envelope can be ejected. Indeed, reference 35 calculates that for stars $< 3M_\odot$ with cores $> 0.86\ M_\odot$ at peak surface luminosity following a helium-shell flash, radiation pressure within the envelope was sufficient to eject it. Other factors which may have some bearing on the lower than expected numbers of bright AGB stars are the effects on convective overshoot, variations in the stellar birthrate function, and hot envelope burning of the dredge-up carbon. Studies of stars leaving the AGB are given in references 36 and 37.

Finally, detailed observations are being made of both the elemental and isotopic abundance in AGB stars. Examples of such studies can be found in references 38-41. Besides providing qualitative agreement with some of the predictions of the stellar evolution models these detailed observations also provide interesting points of disagreement which will require further theoretical study.

IV. SUMMARY

For AGB stars there is a fair agreement between theory and observation, but many details need to be worked out. AGB stars are observed to exist and they provide direct evidence of the third dredge-up phase bringing up ^{12}C and S-processed elements to the surfaces of stars where by mass loss these products are released into the interstellar medium for further recycling into the next generation of stars. Whether the integrated effect of AGB stars of all masses can reproduce the observed solar system distribution of elements remains to be determined. In any case AGB stars should be an important contributor of ^{4}He, ^{12}C, and some S-processed elements to the Galaxy.

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